Does the Blazar Gamma-ray Spectrum Harden with Increasing Flux? - Analysis of Nine Years of EGRET Data.

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ABSTRACT

The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO) discovered gamma-ray emission from more than 67 blazars during its nine-year lifetime. We conducted an exhaustive search of the EGRET archives and selected all the blazars that were observed multiple times and were bright enough to enable a spectral analysis using standard power-law models. The sample consists of 18 flat-spectrum radio quasars (FSRQs), 6 low-frequency-peaked BL Lacs (LBLs) and 2 high-frequency-peaked BL Lacs (HBLs). We do not detect any clear pattern in the variation of spectral index with flux. Some of the blazars do not show any statistical evidence for spectral variability. The spectrum hardens with increasing flux in a few cases. There is also evidence for a flux-hardness anticorrelation at low fluxes in five blazars. The well observed blazars (3C 279, 3C 273, PKS 0528+134, PKS 1622-297, PKS 0208-512) do not show any overall trend in the long-term spectral dependence on flux, but the sample shows a mixture of hard and soft states. We observed spectral hysteresis at weekly timescales in all the three FSRQs for which data from flares lasting for 3∼4 weeks were available. All three sources show a counter-clockwise rotation despite the widely different flux profiles. Hysteresis in the spectral index vs. flux space has never been observed in FSRQs in gamma-rays at weekly timescales. We analyze the observed spectral behavior in the context of various inverse-Compton mechanisms believed to be responsible for emission in the EGRET energy range. Our analysis uses the EGRET skymaps that were regenerated to include the changes in performance during the mission.

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1. Introduction

Blazars are a class of Active Galactic Nuclei (AGNs) characterized by highly luminous and rapidly variable continuum emission at all observed frequencies from radio to gamma-rays. VLBI structures of these sources reveal compact cores with jet-like features which often show evidence of superluminal motion (Vermulen & Cohen 1994). The broadband spectral energy distribution (SED) of these sources shows two peaks. It has been widely accepted, in the scenario of leptonic models, that the lower-frequency peak is due to synchrotron emission from relativistic plasma moving along the jet away from the core of the AGN while the second peak is attributed to inverse-Compton scattering of relativistic electrons by soft ambient photons, produced either internal or external to the jet. These "seed-photons" for inverse-Compton emission could come from synchrotron emission itself as postulated by synchrotron-self Compton (SSC) models (Ghisellini et al. 1985; Maraschi, Ghisellini & Celotti 1992; Marscher & Gear 1985; Bloom & Marsher 1996), or they could be entering the jet directly from the accretion disk as in the ECD (external Compton scattering of direct disk radiation) models (Dermer, Schlickeiser & Mastichiadis 1992; Dermer & Schlickeiser 1993), or they could reach the jet after being re-scattered by surrounding broad-line-region (BLR) clouds as in the ECC (external Compton scattering from clouds) models (Sikora, Begelman & Rees 1994; Blandford & Levinson 1995; Dermer, Sturner & Schlickeiser 1997). In addition, the BLR could also reflect the synchrotron photons back into the jet to undergo inverse-Compton scattering (External-Reflection-Compton model; Ghisellini & Madau (1996)). Finally, the seed photons could be produced by the infrared (IR) dust that surrounds the blazar nucleus (External Compton from infrared dust-ERC(IR); Sikora et al. (2002); Blazejowski et al. (2000)). The dust is more concentrated in a torus that lies in the equatorial plane of the blazar (Wagner et al. 1995). Quite often, a combination of these models is required to fit the broadband spectrum of a blazar through the entire range of frequencies from radio to gamma-rays.

Observationally, the class of blazars includes flat-spectrum radio quasars (FSRQs) and BL Lac objects. FSRQs have strong and broad optical emission lines while the lines are weak in BL Lac objects. The position of the peaks in a broadband SED allows a further division of BL Lac objects into two categories: low-frequency-peaked BL Lacs (LBLs) and high-frequency peaked BL Lacs (HBLs). The first peak is at infra-red/optical frequencies for *red blazars* which could be either the FSRQs or the Low-frequency-peaked blazars (LBLs) and

at UV/X-rays for *blue blazars* or the High-frequency-peaked blazars (HBLs). The second peak is in the gamma-ray range (MeV-GeV) for LBLs & FSRQs and in the TeV range for HBLs. HBLs are much lower in overall luminosity than FSRQs with LBLs somewhere between (Fossati et al. 1998).

During its nine year lifetime, EGRET has detected GeV-range emission from more than 67 blazars and a number of them have been observed multiple times (Hartman et al. 1999;3EG). The EGRET energy range (30 MeV-10 GeV) lies near the maximum or on the falling portion of the inverse-Compton peak for FSRQs and on the rising portion of the peak in the case of HBLs and it lies somewhere in between for LBLs. A continuity in the observed spectral properties of BL Lacs and FSRQs has been postulated by Fossati et al. (1998) with the gamma-ray spectral index getting progressively harder from FSRQs to HBLs. While this trend is expected of the average spectral properties of these sources, previous studies have suggested a hardening of the gamma-ray spectral index in FSRQs with an increase in flux. This was reported for individual blazars in Mukherjee et al. (1995); Sreekumar et al. (1996); Bloom et al. (1997); Stacy et al. (2003) and was also observed in the combined data from 18 brightest blazars (Sreekumar et al. 2001). This feature, coupled with the fact that the average spectral index of 2.15 ± 0.04 measured for blazars (Mukherjee et al. 1997) is quite close to the spectral index of 2.10 ± 0.03 (Sreekumar et al. 1998) for diffuse gamma-ray background, is used to attribute the extragalactic gamma-ray background to emission from unresolved blazars (Stecker & Salamon 1996).

With the EGRET's calibration finalized and its archive now complete, the behavior of gamma-ray spectral index can be studied in detail across different epochs and over a broad range of flux. This paper presents the results of such an effort and is organized as follows. We reanalyzed the entire blazar data from the EGRET mission for this project. Section 2 describes the data and § 3 discusses the analysis procedure. We examine the spectral properties of different source classes, the long term and the short term spectral variability in § 4, discuss the implications of the results in § 5, and summarize in § 6.

2. Source Selection and Observations

CGRO was launched on April 5 1991 and it re-entered the earth's atmosphere on June 4, 2000. One of the four instruments on board was EGRET that was sensitive in the energy range 30 MeV-10 GeV. The Third EGRET Catalog (Hartman et al. 1999;3EG) contains the basic results (flux and spectral indices) from analysis of all observations till the end of Cycle 4 (October 3 1995). Mukherjee et al. (1997) presented summary results for all blazars detected through the end of Cycle 4 and included the spectral indices for blazars that were

detected at a significance greater than 6σ. Although there were very few new detections after Cycle 4 (e.g. PKS 2255-282, Mrk 501), 8 blazars were observed multiple times in Cycles 5-9. Spectral analysis results after Cycle 4 are available only for PKS 0528+134 (Mukherjee et al. 1999), which contains results through the end of Cycle 6.

EGRET viewing periods (VP) ranged in duration from 3 to 20 days but they were usually a week long. Sometimes an object was observed during two or more contiguous viewing periods as a part of the observing schedule or because the object was in an extremely active state. EGRET was operated with a narrow field of view for most of the latter half of the mission (Cycle 5 onward) to conserve gas lifetime, thus limiting the number of accessible targets. The details (viewing period number, start and end dates, field of view mode-normal/narrow) of the viewing periods (after Cycle 4) are listed in columns 1-4 of Table 1. Columns 4 & 5 list the sources that were in the field of view (FOV) during that time, and their off-axis viewing angle respectively. Information for viewing periods prior to Cycle 5 are listed in 3EG.

We have analyzed all nine years of data for all the blazars seen by EGRET, and these objects are listed in Table 2. The sample consists of 97 sources, 67 of which are confirmed identifications. The thirty "possible" identifications are marked by a "?" in column 2, and the more common names of the sources are listed in column 3. The distribution consists of 66 flat-spectrum radio quasars (FSRQ), 17 low-freqquency peaked BL Lacs (LBL), 3 high-frequency peaked BL Lacs (HBL), 10 flat-spectrum radio sources (FSRS) and 1 radio galaxy. The classifications (listed in column 10 of Table 2) have been adopted from Hartman et al. (1997) and Ghisellini et al. (1999). The 66 flat-spectrum radio quasars have been further classified into 19 high-polarization quasars (FSRQ(HP)), 15 low-polarization quasars (FSRQ(LP)). Polarization information could not be obtained for the remaining. Twenty-six of the 97 sources were observed multiple times and were bright enough during those observations to yield a spectral index. These sources are marked by a "Y"in column 9.

3. Analysis

EGRET was a spark chamber telescope with an effective area of 1000 cm^2 at 150 MeV, 1500 cm^2 between 500 MeV-1 GeV, decreasing gradually to about 700 cm^2 at 10 GeV. The off-axis sensitivity decreased as an approximate Gaussian with a full-width-half-maximum of $\sim 20^o$. The sensitivity beyond 30^o was less than 15% of the on-axis sensitivity. Details of the instrument and calibration can be found in Kanbach et al. (1988); Hughes et al. (1980); Thompson et al. (1993); and Esposito et al. (1999). During its nine year lifetime, the spark chamber gas was refilled multiple times (Bertsch et al. 2001), and for most of the latter

half of the mission (Cycle 5 onward), EGRET was operated with a narrow field of view (18^o useful radius) to conserve gas lifetime. The detection efficiency of EGRET varied throughout the mission due to aging of the spark-chamber gas between refills and a hardware failure in 1997. An energy dependent effect was also observed in the degradation. The method used to calibrate the efficiency up to Cycle 4 (Esposito et al. 1999) did not deal with this energy-dependence adequately. The results in this paper are derived from EGRET maps produced using the calibration described in Bertsch et al. (2001).

One of the standard EGRET data products for any viewing period is a pair of maps showing gamma-ray arrival directions from the observed sky-region in the energy intervals 30-100 MeV and 100-10000 MeV. For the work presented here, these maps were used in conjunction with a list of all the known EGRET-sources, to determine simultaneously the counts from all sources in the field of view and their significance of detection in the two energy-intervals through a method of maximum likelihood. Details of the maximum likelihood method and the process of determination of the significance of detection can be found in Mattox et al. (1997) and Esposito et al. (1999). All sources that were detected at a significance $< 2\sigma$ in the energy interval 100-10000 MeV were eliminated from the list and the process was repeated again to determine the counts and fluxes (along with the associated errors) for the remaining sources.

If the source of interest was detected at a significance $> 4\sigma$ in the energy interval 100 MeV-10000 MeV, then a four point spectrum was determined using counts recorded in the energy intervals (in MeV) 30-100, 100-300, 300-1000 & 1000-10000. The points were fitted with a single power law of the form $F(E) = k(E/E_o)^{-\alpha}$ photons cm^{-2} s^{-1} MeV^{-1} where $F(E)$ is the flux, α the photon spectral index, E the photon energy, E_o the energy normalization factor and k a coefficient of normalization.

If the overall significance of detection of the source was greater than 6σ, the energy intervals with a strong detection were further split up into smaller intervals (for which standard EGRET maps exist) to determine the spectral index. For the strongest sources, the standard 10 intervals 30-50, 50-70, 70-100, 100-150, 150-300, 300-500, 500-1000, 1000-2000, 2000-4000, 4000-10000 (all in MeV) were utilized. Most of the spectra after Cycle 5 had to be determined using 4-5 energy intervals (when a source was not undergoing a flare). Figure 1 shows sample four-point spectra from PKS 1622-297 and a 5-point spectrum from 3C 279. Analysis using the new maps has constrained the spectral indices better (lower errors) for a majority of the sources. Previous EGRET spectral analyses required a minimum of 6-sigma significance of source detection and used 10 energy bins to calculate the spectrum. We have used a slightly different approach, lowering the cutoff to 4 sigma. This does not affect the quality of the spectral analysis since we are using only 4-5 energy intervals for computing

the spectral indices for faint sources, giving us better statistics in each bin, and lowering the errors. In addition, we found that the spectral index was within the error bars of the index calculated using 10 energy bins.

Some of the blazars considered here were part of extended campaigns. If the source was not very bright during such times, adjacent viewing periods were combined. The analysis process was then repeated with the combined data, and an attempt was made to extract the spectrum. The longest period for which a source was in EGRET's field of view continuously was 49 days (7 viewing periods), for 3C 273 and 3C 279. Sometimes, all the observations during a cycle had to be combined to obtain a reliable detection and spectrum.

We have done a complete spectral analysis for all the blazars detected by EGRET using the recalibrated data products. Table 2 (column 6) shows their average photon spectral indices. For the bright blazars that were observed multiple times, we used the sample mean and standard deviation (of mean) as the spectral index. For the rest, we used the spectral index from all the data available unless a source was bright during one of the observations and was almost inactive during the rest of the viewing periods. Column 7 lists the mean flux ($>$ 100 MeV) recorded for these sources in units of 10^{-8} photons cm^{-2} sec^{-1}. Table 3 lists the results of spectral analysis for sources which yielded more than one spectral index value. Columns 5, 6 & 7 list the spectral index, flux and the detection significance, respectively. The viewing periods that were combined to get the spectra are listed in column 3 while their corresponding starting dates are listed in column 2 in the same order. For identification purposes, each of these observations is labeled in the spectral index vs. flux plot shown in Figure 3, with the labels listed in column 4 of Table 3.

4. Results

4.1. Gamma-ray spectral distribution

Since a classification of blazars was based on the location of the synchrotron peak, we searched the literature for multiwavelength fits to data from all the blazars detected by EGRET, in order to determine the frequency of their synchrotron peaks and to examine its dependence on the gamma-ray spectral index. Multiwavelength fits to the broadband spectrum ($log(\nu F_\nu)$ vs $log(\nu)$) from simultaneous data are available for more than one epoch for: 3C 279 (Hartman et al. 2001; Ballo et al. 2002), BL Lac (Böttcher & Bloom 2000), 3C 273 (Kataoka et al. 2002), PKS 2155-304 (Chiappetti et al. 1999; Kataoka et al. 2000), Mrk 421 (Aharonian et al. 2001; Takahashi et al. 2000; Krawczynski et al. 2001), Mrk 501 (Tavecchio et al. 2001; Kataoka et al. 1999; Krawczynski et al. 2002; Petry et al. 2000), PKS 0528+134

(Mukherjee et al. 1999). For the rest of the blazars, we used values from Ghisellini et al. (1999) & von Montigny et al. (1995) that are compilations of multiwavelength data (simultaneous and non-simultaneous) from literature and corresponding broadband model-fits. In cases where there is more than one fit available, or when a clear determination of the peak was not possible, the peak frequency was fixed at the average value and the error was calculated from one of the extremes. The logarithm of synchrotron peak frequency values have been listed in column 8 of Table 2.

The plot of gamma ray spectral index vs log synchrotron peak frequency for the blazars in our sample is shown in Figure 2. The sample of sources shown in the plot consists of 37 FSRQs, 10 LBLs and 3 HBLs. The blazars for which we could not find the synchrotron peak frequency in the literature have been excluded from the figure. Since FSRQs have the lowest synchrotron-peak frequency and the EGRET energy range lies on the decreasing portion of their inverse Compton peak (in a plot of the broadband spectral energy distribution), they are expected to have soft spectral indices. HBLs have the highest synchrotron peak frequency and the EGRET-range lies on the rising portion of their inverse Compton peak. Consequently, they are expected to have hard spectral indices. LBLs lie somewhere in between. Under this unified-blazar paradigm, a plot of gamma-ray spectral indices vs. synchrotron peak frequencies should have a smooth variation from FSRQs to LBLs to HBLs (Fossati et al. 1998). A plot similar to that shown in Figure 2 was made in the past for 27 blazars using data through Cycle 4 (Lin et al. 1999). A comparison of our data with this work shows that some of the spectral indices obtained by us are different, due to the availability of more data and the recalibration of the raw data products, as described earlier (see section 3).

We obtained a mean spectral index of 2.26 ± 0.03 for the 66 FSRQs, 2.14 ± 0.08 for the 17 LBLs, 1.68 ± 0.09 for the 3 HBLs and 2.48 ± 0.1 for the 10 other flat spectrum radio sources (FSRS). The spectral index for FSRQs with high polarization (HP) and low polarization (LP) was 2.19 ± 0.06 and 2.32 ± 0.06 respectively. The spectral index increases across HBLs, LBLs, FSRQs(HP) and FSRQs(LP). This is consistent with the prediction that the spectral properties of blazars form a well defined sequence from HBLs to LBLs to FSRQs (HP,LP) (Ghisellini et al. 1999; Fossati et al. 1998).

4.2. Spectral variability with Flux

4.2.1. Long term spectral variability

We searched for variability in the spectral index of all the blazars (for which two or more spectral indices could be calculated) using the χ^2 test and the results are listed in Table 4. Column 2 contains the sample mean (Γ_μ) and the standard deviation of the mean (σ) for each blazar. The χ^2_{red} value obtained from fitting the sample of spectral indices with a line of constant mean Γ_μ is listed in column 3. Column 4 lists the degrees of freedom (DOF) (which is one less than the sample size), while column 5 contains the confidence level for the presence of spectral variability. We do not detect any statistical evidence for spectral variability in 16 of the 26 blazars. The confidence levels for the presence of spectral variability are low ($< 80\%$), mostly due to the large error bars on the spectral indices.

We looked for spectral variability correlated with flux using the Pearson's correlation coefficient. The correlation coefficient is listed in column 5 of Table 4. The coefficient, which could be calculated only in cases where there were three or more observations, is negative when the spectral index (positive) hardens with increasing flux. The dependence of spectral index on flux is not uniform across all the blazars. The index hardens with increasing flux in some cases, softens in others, and in the rest does not vary with flux. Using a cutoff of 0.8 for the correlation coefficient, we found the spectral index to be correlated with flux in 10 of the 26 blazars (including those with two observations where there was visual evidence). The spectrum hardened with increasing flux in 6 of them while the spectrum softened in the remaining 4. Only five sources satisfied both the spectral variability and the index-flux correlation criteria: PKS 0537-441, 1222+216 (4C 21.35), PKS 1633+382 (4C+38.41), 2200+420 (BL Lac) and 2230+114. We discuss some individual sources below.

1253-055 (3C 279): This object shows spectral variability at a confidence level of 99.99% and shows marginal evidence for hardening with increase in flux. The spectral states at a flux $> 70 \times 10^{-8}$ photons cm^{-2} s^{-1} span more than 85% of the range of fluxes observed. These states do not show any overall trend in the spectral index vs. flux space (correlation coefficient of 0.05) and do not show any significant evidence for spectral variability (confidence level of 58%). The quiescent states from Cycles 3 and 4 have a softer spectral index when compared with the average value of 1.96 while the quiescent state from Cycle 6 has a harder spectral index.

PKS 0208-512: We do not see any overall trend for this source, in spite of a strong evidence for spectral variability (confidence of 98%). However, the spectral index does show evidence of hardening with increasing flux (correlation coefficient of -0.95) at fluxes higher than 60×10^{-8} photons cm^{-2} s^{-1}. A similar trend was also observed in this source by Stacy

et al. (2003) who combined simultaneous data from the Compton Telescope (COMPTEL; 0.75-30 MeV) and EGRET. They obtained a correlation coefficient of -0.78 between the spectral index in the 0.75 MeV - 10 GeV range and the flux (>100 MeV) recorded in the EGRET energy range.

We observe a softening in the spectral index (coefficient of +0.95) as the flux increases, at fluxes lower than 80×10^{-8} units. There is an indication of this effect at lower fluxes in Stacy et al. (2003, see Figure 4), but the large error bars do not justify a separate fit. Moreover, PKS 0208-512 has been categorized as an "MeV-blazar" and the spectrum from these sources shows a break between 1-20 MeV (Sikora et al. 2002; Skibo et al. 1997; Blom et al. 1995; Collmar et al. 1997). Hence, a single power law does not adequately describe the entire energy range form 0.75 MeV-10 GeV. Flux anti-correlations between COMPTEL and EGRET could also be expected for MeV-blazars (observed in case of PKS 0528+134, also a possible MeV blazar; Collmar et al. (1997)). But a reanalysis of the 1993 COMPTEL data by Stacy et al. (2003) lowered the significance of the only detection of this source in the MeV energy range, with no detections in its many subsequent observations. Consequently, the association of PKS 0208-512 with MeV-blazars is questionable. But the unique nature of the spectral dependence on flux (initial softening and subsequent hardening) in the EGRET energy range, makes this strong gamma-ray source an interesting candidate for future observations.

PKS 0528+134: Previously published results for this object (Mukherjee et al. 1996) showed a correlation of -0.85 between spectral index and flux using data from viewing periods 0.2-0.5 (combined), 1.0, and 213.0. The same combination of viewing periods using recalibrated data did not show any evidence of spectral hardening. Inclusion of data through viewing period 420.0 decreased the correlation to -0.5 (Mukherjee et al. 1999). We obtained a correlation coefficient -0.5 for the complete data which included observations from Cycles 5 and 6. The large error bars yield a low confidence of spectral variability of 67% despite a spread in the values.

PKS 0537-441, PKS 1633+382 (4C+38.41): Spectral indices for these objects harden with increasing flux (correlation coefficients of -0.97 & 0.99) and show spectral variability at a confidence of 87% and 98% respectively.

2200+420 (BL Lac) & 2230+114 (CTA 102): The spectrum hardens with increasing flux in these sources. The correlation coefficient was not calculated in these cases as there were only two observations.

Some of the FSRQs and LBLs show spectra that appear to soften with increasing flux. This can be seen in PKS 1222+216 (4C 21.35), PKS 1219+285 (ON 231), and, also in PKS 0208-512 and S5 0716+714 at low fluxes.